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MODELING PILOT EXPERTISE IN AIR COMBAT

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This report documents two presentations on air combat performance measurement research. The first, Modeling Pilot expertise in Air Combat, was presented at and published in the Proceedings of the Human Factors Society 36th Annual Meeting in Atlanta, GA, which was held on 12-16 October 1992. This presentation discussed an effort to model expert pilot performance and decision making in one-versus-one (1V1) air-to-air combat. The second, Validating a Model of Air Combat Expertise, was presented at and published in the proceedings of the 14th Biennial Applied Behavioral Sciences Conference, 6-8 April 1994, at Colorado Springs, CO. It descibes the Intelligent System for Air-to-Air Combat (ISAAC) which was developed to model expertise in 1v1, within-visual-range, air combat. ISAAC was developed based upon a subject matter expert's verbal protocol provided in structured interviews and in protocols collected both during and after simulated combat engagements flown in the Simulator for Air-to-Air Combat (SAAC).

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PREFACE

The research described in this report was conducted at the Armstrong Laboratory, Human Resources Directorate, Aircrew Training Research Division (AL/HRA), in Mesa, Arizona, under Work Unit 2743-25-17, Flying Training Research Support. The work was conducted under Contract F33615-90-C-0005 with the University of Dayton Research Institute (UDRI). The laboratory contract monitor was Ms Patricia Spears; task monitor was Dr Wayne L. Waag.

This report includes documentation of research performed on air combat performance measurement. Results of the research on modeling pilot expertise in air combat was presented at the 36th Annual Meeting of the Human Factors Society, held from 12-16 October 1992, in Atlanta, GA. Subsequent research on validation of the model was presented at the 14th Biennial Applied Behavioral Sciences Conference, from 6-8 April 1994, in Colorado Springs, CO. The presentations were also published in the respective proceedings.

MODELING PILOT EXPERTISE IN AIR COMBAT

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The purpose of this effort was to model expert pilot performance and decision making in one-versus-one (1v1) air-to-air combat. Several knowledge-elicitation techniques were used to extract air combat expertise from a former fighter pilot, who served as the subject-matter-expert (SME). Unstructured and then structured interviews were used to elicit the goals and sub-goals of air-to-air combat, plus some of the pilot behaviors necessary to accomplish the goals. The SME also flew a number of combat sorties against another former fighter pilot in the Simulator for Air-to-Air Combat (SAAC) to demonstrate pilot performance required to accomplish the goals of air combat. Based on the SME's verbal protocols, a group of air combat rules were developed. A rule-based production system was then designed to incorporate the resulting knowledge base. The production system was also designed to be capable of analyzing an existing data base of air combat engagements. Expert system development required additional input from the SME to identify specific values of flight parameters required by the production system. Upon completion and SME verification of the expert model, it will be validated by comparing its performance to that of our SME in simulated air-to-air combat. If the model can successfully describe expert pilot performance, the model will be used to provide diagnostic performance feedback in conjunction with SAAC training.

Air combat performance measurement research has resulted in several varieties of pilot performance measures. These include measures of position advantage (e.g., McGuiness, Forbes, and Rhoads, 1984; Wooldridge, Kelly, Obermayer, Vreuls, Nelson, and Norman, 1982), energy maneuverability (e.g., Pruitt, 1973; Pruitt, Moroney, and Lau, 1980), and critical discrete events (e.g., Brictson, Ciavarelli, Pettigrew, and Young, 1978; Ciavarelli, 1987). The Armstrong Laboratory, Aircrew Training Research Division (AL/HRA) has developed and implemented the Air Combat Maneuvering Performance Measurement System (ACM PMS) which has the ability to collect, analyze, and display many of these measures taken from simulated combat performed on the Air Combat Maneuvering Instrumentation (ACMI) range and in the Simulator for Air-to-Air Combat (SAAC) at Luke Air Force Base, Arizona. AL/HRA has also validated some of these measures (Waag, Raspotnik, and Leeds, 1992); however, the measures provide little diagnostic value to the individual pilot and cannot describe the underlying decision-making and cognitive processes used by pilots.

In an attempt to formulate diagnostic measures of air combat performance and to better understand the underlying cognitive and decision-making processes required, AL/HRA initiated a project to investigate pilot expertise in one-verses-one (1v1), air-to-air (A/A) combat. The objective of the effort was to develop a performance model of expert pilot behavior in air combat. The model would serve as a standard for air combat performance, and actual pilot performance that deviated from that standard would serve as data for diagnostic measures of pilot performance. This paper describes various procedures used to elicit air combat

knowledge from a subject matter expert (SME). Several procedures were used to determine which would be most effective for future knowledge elicitation work. The knowledge base elicited by these methods was then incorporated in a descriptive model of expert air combat performance. After more specific values for air combat parameters were obtained from the SME, the knowledge base was coded in the form of a rule-based expert system.

KNOWLEDGE ELICITATION METHODOLOGY

Subject Matter Expert

The SME is a former F-4 pilot with combat experience. He had been director of the SAAC and responsible for its operation, maintenance, and upgrade to the current F-15 and F-16 configuration. The SME has flown more than 500 engagements in the SAAC against pilots ranging in proficiency from novice to expert.

Knowledge Elicitation

Several knowledge elicitation methods were employed. Initially, the SME was interviewed to obtain the top level goals of air combat maneuvering, plus the subgoals and operators which allow the pilot to achieve those goals. Goals include: Place the opponent in your cone of fire while remaining outside your adversary's cone of fire. Subgoals include: Turn faster than your opponent and point your aircraft in the direction of your opponent. Operators to accomplish these goals include: Turn in the direction of the opponent, place him on the plane of the vertical stabilizer (PVS), and pull him to your nose. A second more structured interview was conducted to identify additional operators required to accomplish the goals of air combat.

The SME also flew a series of 1v1 air combat engagements against an another former fighter pilot in the SAAC. Each pilot began the engagements in either an offensive, defensive, or neutral position. Total time in the simulator was about one hour. Immediately after simulator sessions, the engagements were replayed on the ACM PMS. The SME was videotaped as he debriefed his own performance during replays, describing his goals, actions to meet those goals, and the necessary conditions for initiating those actions. This information was used to confirm data collected in the interviews, to elaborate and refine the goals and operators, and to determine which operators were appropriate under what circumstances. From a methodological standpoint, this procedure appeared appropriate to meet the aforementioned objectives; however, it was noted that the SME occasionally confused air combat engagements. This was not unexpected since his behavior was similar in several engagements, and the time between engagements and debriefing those engagements usually exceeded one hour. This knowledge elicitation procedure may be appropriate for identifying general principles of air combat and specific instances where air combat rules apply, but may not be ideal for investigating specific pilot decisions during air combat.

Two similar knowledge elicitation procedures were then used to add more air combat rules to the database. The SME was audio taped as he identified his air combat goals, his actions to achieve those goals, and the situational variables that dictated those actions. The SME again flew a number of engagements against the same former fighter pilot in the SAAC using the same initial conditions as before. In one condition, the SME described what he was doing and why, while flying in the SAAC, and in the other condition he did so immediately after flying each engagement. These methods resulted the identification of a set of situational assessment variables such as nose position, closure, energy, aspect, range, and altitude; specification of additional air combat rules; and identification of more instances where the rules apply. It was noted that performing in the SAAC occasionally interfered with the SME's ability to describe and interpret his actions. In the other condition, where the SME debriefed after engagements, he occasionally forgot details of the air combat.

A final procedure was used to refine situational assessment variables, to elaborate and refine air combat rules, and to identify specific instances where rules apply in achieving the stated goals of air combat. The SME again flew a number of air combat engagements in the SAAC against the same former fighter pilot. In this condition, opponents did not describe their actions until the end of each engagement. Engagements were replayed in the SAAC so that opponents could see each engagement recreated to include all in-cockpit displays and out-of-cockpit visuals. There is also a freeze capability in the SAAC's replay function. This allowed the SME to freeze the replay so he could fully elaborate on what he had done and why. SME comments were again audio taped. As would be expected, this condition placed the least demands on the SME's memory, and with the absence of the competing task of flying, afforded him ample time to describe the rationale behind his air combat behaviors. This procedure will be used in the future to elicit knowledge for additional SMEs.

The information obtained from the above procedures was compiled and modeled, and then

provided to the SME for critique and review. He provided additional detail to existing rules and additional air combat rules that were not derived using the previously described methodologies. The final set of rules was then prepared for inclusion in a rule-based production system.

PRODUCTION SYSTEM DEVELOPMENT

The purpose of production system development was to provide a model of expert performance in F-15 and F-16 air combat. A requirement of the expert system was that it be capable of interfacing with the SAAC database which includes 500 engagements between our SME and 125 pilots. The expert system, named ISAAC (Intelligent System for Air-to-Air Combat) was to include a performance measurement and critiquing capability, and be easily validated using SAAC engagement data. Validation testing would include determining if the SME actually followed his own rules, and if the model could predict air combat winners and losers, and expert and novice pilots.

The initial ISAAC model described the first several "moves" appropriate for the line abreast initial condition where opponents start at co-altitude, 6000 feet apart. The appropriate things to do, according to the SME, are to turn in the direction of the adversary until the opponent aircraft appears on the plane of the vertical stabilizer (PVS) (a plane that extends from the nose to the tail of an aircraft), and then pull hard on the stick, so as to point the aircraft at the adversary. Assuming both opponents do the same thing (if one does not, he will be at a significant disadvantage), the line abreast condition will convert to a near head-on condition. If one of the opponents achieves a significant aspect angle advantage as a result of making a smaller initial turn, that pilot should reverse the bank of his aircraft to maintain visual contact with the other aircraft. He should then begin a lead turn before the airplanes pass head-on. This set of actions will give the lead-turning aircraft an additional aspect angle advantage on the next head-on pass.

The above example was coded using the expert system shell, PCPlus. This shell requires production rules that define appropriate aircraft maneuvers, additional rules to define these maneuver rules in terms of aircraft state parameter data, rules to search the database to determine if state parameters requirements have been satisfied, and rules that report if aircraft maneuvers have been performed correctly. The resulting expert model is, therefore, a hierarchy of rules and specifications to include goals, top-level rules, translation rules, parameter definitions, special default provisions, and software to process engagement data. ISAAC is primarily a backward chaining inference system that proceeds backward from specified goals, chaining through the applicable rules to determine if the goal was satisfied. Examples of goals include: a maneuver goal, to test if pilot maneuvering conforms to the SME rules, and goal reporting, to ensure that output required for future analyses is recorded.

Top-level rules infer a yes/no value for each of the goals. Maneuver rules are defined in terms of more than one specific pilot action, as described by the SME. These rules determine if a particular maneuver was performed when the SME considered it appropriate to do so.

<u>Rule 11</u>
Subject: Maneuver 1 Rules
If : (Roll_Toward_Bogey_Man1 And Bogey_On PVS_Man1 And Max_G_Man1)
Then: (Turned_Into_Bogey)

Top-level rules use terms which require further definition to determine values in terms of available engagement data. For example, statements such as "roll toward the bogey" and "on the PVS" require <u>translation rules</u> that specify the behavior that defines the top-level rules. Defining these translation rules often required additional interaction with the SME, since the content of these rules is only implied by top-level rules.

<u>Rule 23</u>
Subject: Translate-To-Data-Man1-Rules
If: ((Left_Abreast And Aroll_F_2 < 0 And Aroll_F_4 < 0) or (Right_Abreast And Aroll_F_2 > 0 And Aroll_F_4 >0))
Then: (Roll_Toward_Bogey_Man1)

A third level of the expert system is parameter definitions. The parameters are used by the translation rules and must be defined for the expert system. Parameters are defined by such values as number, positive number, string, and single- or multi-valued. Parameters also identify data from the air combat engagement file by file name and location in the file.

<u>Aroll_F_2</u>
Translation: (Roll Angle, A/C 1, 1/4 Betw Start And CPA1)
Type: Singlevalued
Used By: (Rule023)
Method: (Dos-File-In PCFILE.11 Index 58)

Due to the idiosyncrasies of PCPlus, some additional information must be provided by giving specific values to parameters. This "special case" is an output message parameter where a value is the message.

If a yes value for a yes/no parameter or goal cannot be established, PCPlus will infer "don't know"; or if unable to establish a "yes" value should result in a "no" value, then the parameter must be given a "no" default value.

Man1
Translation: (Maneuver Segment 1 Appropriate?)
Type: Yes/No
Updated-By: (Rule010 Rule055)
Used-By: (Rule033 Rule042 Rule009)
Default: (No)

Software was developed to pre-process air combat engagement data for use by the expert system. A "C" program was developed to process SAAC engagement files into a form suitable for ISAAC. This program encodes engagement file data in the format required by ISAAC; parses time history files into segments corresponding to commonly occurring events such as start, first merge, second merge, and various typical aircraft maneuvers; and provides computations for variables such as "on the PVS," "bogey in view," "percent of time in cone of fire," and percent of time offensive, defensive, or neutral.

Subsequent work involved adding air combat rules to the existing knowledge base, refining and testing those rules, and partitioning the knowledge base into frames corresponding to commonly occurring segments of air combat. The first frame includes rules describing initial conditions, rules required to bring the adversaries to the first merge, and rules that apply at and immediately following the merge. Since air combat often involves a series of near head-on passes, the second frame includes rules that describe a series head-on passes. Frames were also developed to include rules that indicate what the pilot should do when he is either offensive or defensive with respect to the adversary. A final frame was developed to include rules that apply when neither pilot is offensive and both aircraft are in close proximity.

Initial ISAAC validation will determine the degree to which the performance of the model compares to that of our SME. ISAAC includes nearly 300 production rules, but only two dozen are primary maneuver rules. These rules specify a particular course of action that is appropriate for a given set of circumstances within offensive, defensive or neutral frames. ISAAC takes as input pilot data from the SAAC and outputs a report as to whether or not the pilot performed the appropriate maneuver. To determine the degree to which SME performance matches ISAAC rules, a percent "correct" was calculated for each maneuver rule across the 500 SAAC engagements. A second validation test was performed to determine if ISAAC could predict air combat winners versus losers and novice versus expert performance. It was predicted, of course, that winners and experts would perform more in accordance with ISAAC than would losers and experts. Adversary performance in the SAAC, rather than SME performance, was compared to that of ISAAC. Again, a percent concurrence between pilot and model was calculated for each ISAAC maneuver rule.

ISAAC rules will be refined further as a result of validation tests, and additional SMEs will evaluate the adequacy and accuracy of the ISAAC rule base. When the system has been finalized, it will be integrated with the ACM PMS to provide post-mission diagnostic feedback to pilots training in the SAAC.

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VALIDATING A MODEL OF AIR COMBAT EXPERTISE

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Abstract

The Intelligent System For Air-To-Air Combat (ISAAC) was developed to model expertise in one-verses-one (1v1), within visual range, air combat. ISAAC incorporates the air combat rules of a subject matter expert (SME) within a typical expert system architecture. Prior to implementing the system in a training environment, it was necessary to validate ISAAC. To represent expertise in air combat, such a system should accurately portray the behavior of the expert who is the source of the expertise. It is also expected that pilots who follow ISAAC rules should perform better in air combat than those who do not. To test ISAAC, data were taken from the Simulator for Air-to-Air Combat (SAAC) in which Air Force pilots flew 1v1 engagements against the expert and analyzed by ISAAC to determine the degree to which pilots followed ISAAC rules. Results indicate that the expert followed his own rules nearly 80% of the time, whereas his opponents followed the rules 66% of the time. All pilots followed ISAAC rules more often when they won air combat engagements than when they lost.

The Intelligent System for Air-to-Air Combat (ISAAC) is a rule-based production system that models expert pilot performance and decision making in one-versus-one (1v1), within visual range, air-to-air combat. ISAAC was developed based upon a subject matter expert's (SME) verbal protocols provided in structured interviews and in protocols collected both during and after simulated combat engagements flown in the Simulator for Air-to-Air Combat (SAAC).

According to the SME, the first several "rules" appropriate for the line-abreast setup are the following: the fighter should roll in the direction of the bogey until the opponent aircraft appears on the plane of the vertical stabilizer (PVS) (a plane that extends from nose to the tail of the aircraft), and then pull hard on the stick to effect near maximum Gs. Assuming both opponents do the same thing (if one does not, he will be at a significant disadvantage), the line-abreast condition will convert to a near- head-on condition. If one opponent achieves a significant aspect angle advantage as a result of making a tighter initial turn, that pilot should reverse the bank of his aircraft to maintain visual contact with the

other aircraft. This results in a lead turn before the airplanes pass head-on. The lead-turning aircraft should gain an additional aspect angle advantage on the next head-on pass.

After initial development, data previously collected in the SAAC were analyzed by ISAAC. ISAAC output was then critiqued by the SME, who suggested corrections, additions, and refinements to the system. ISAAC was further developed and refined through repeated iterations of SAAC data analysis and SME critique of ISAAC output. A more detailed description of ISAAC development can be found in Thomas, Obermayer, Raspotnik, and Waag, 1992.

Upon completion and SME verification of ISAAC, analyses were conducted to validate the expert system. Two tests were established to validate the system: The first specified the degree to which the SME followed his own air combat rules as depicted by ISAAC. The second test was designed to determine if air combat winners followed ISAAC rules more often than did losers, and if pilots with considerable fighter experience were more likely to adhere to ISAAC rules than were pilots with little experience in fighter aircraft.

Method

A database containing results of 500 simulated air combat sorties flown in the SAAC was made available for analysis purposes. The SME had flown four engagements each against 125 Air Force pilots, whose experience in fighter aircraft varied from 30 to 2,500 hours. Each engagement started with combatants in a neutral configuration, either line abreast or head on. Engagements concluded when one pilot achieved a "kill" or three minutes time had elapsed.

Procedure 1

The first study was conducted to determine how closely the SME followed his own rules as depicted by ISAAC. Thirty engagements were selected at random from the SAAC database, with the provisions that all were line-abreast set-ups, where the SME won, lost, and drew in each of ten sorties. These 30 engagements were analyzed by ISAAC to determine the degree to which the SME and his opponents followed the air combat rules as specified by the system. The frequency with which pilots followed each of ISAAC's rules was computed for each engagement flown by each pilot within the categories of win, draw, and lose.

Procedure 2

The second study was designed to investigate the effect of adherence to ISAAC rules on the probability of success in air combat and to determine if ISAAC could discriminate pilots with high fighter experience from those with low fighter experience. One-hundred-sixty engagements were selected from the SAAC database. These were the four engagements flown by each of the 20 pilots with the most hours in fighters ($\overline{X} = 1489$ hours)

and the four engagements flown by each of the 20 pilots with the least hours in fighters ($\overline{X}$ = 56 hours). The SME was the opponent in all 160 sorties.

Results

Table 1 shows the frequency and the proportion of opportunities that the SME and his opponents correctly followed ISAAC rules as a function of engagement outcome. For example, when the SME won, he followed ISAAC rules in 89% of the opportunities available. His behavior in air combat more closely approximated the recommendations of ISAAC than did that of his opponents (79% versus 66%). The SME and his opponent's behavior also matched the rules of ISAAC more often when they won (83%) than when they lost (67%) in simulated air combat.

Table 1. Frequency and Proportion of Opportunities that the SME and His Opponents Correctly Followed ISAAC Rules

	Win	Draw	Loss	
SME	.89 (138/155)	.78 (324/416)	.74 (124/167)	.79
Opponent	.77 (98/128)	.65 (184/282)	.60 (96/161)	.66
	.83	.73	.53	

These data were subjected to a SAS logit analysis to test for main effects and interactions. The resulting Wald statistics indicated that the SME followed ISAAC rules significantly more often than did his opponents (χ^2_1 = 27.90, p< .00005), and that a more positive engagement outcome (win) resulted in better pilot adherence to ISAAC rules than did a less satisfactory outcome, such as a loss (χ^2_2 = 20.47, p <.00005). The pilot-by-outcome interaction was not significant.

Table 2 shows the frequency and proportion of opportunities that high-time and low-time fighter pilots followed the air combat rules depicted by ISAAC as a function of engagement outcome. As indicated by the table, pilots who won engagements were more likely to follow ISAAC rules (71%) than pilots who did not (53%). Positive engagement outcome (i.e., win) again resulted in better pilot adherence to ISAAC rules than did less positive outcome (χ^2_2 = 35.03, p< .00005). There was, however, no significant difference in the frequency with which rules were followed by high-time versus low-time pilots (χ^2_1 =.03).

The outcome-by-pilot interaction was significant ($\chi^2_2 = 14.24$, $p < .0008$), as indicated by the fact that low-time pilots followed ISAAC rules slightly more often when they lost than when they tied in simulated combat.

Table 2. Frequency and Proportion of Opportunities that Pilots Correctly Followed ISAAC Rules

	Win	Draw	Loss	
High-Time	**.69** **(185/269)**	**.61** **(442/730)**	**.52** **(626/1215)**	**.57**
Low-Time	**.81** **(43/53)**	**.53** **(376/703)**	**.55** **(843/1535)**	**.55**
	.71	**.57**	**.53**	

In general, SME performance in simulated air combat was superior to that of pilots he opposed. Table 3 indicates the number and proportion of wins, draws, and losses achieved by high and low-time pilots who opposed the SME. As indicated by the table, these pilots defeated the SME in only 12% of the engagements, whereas they lost in 67% of the simulated air combat.

Table 3. Pilots' Number and Proportion of Wins, Losses, and Draws Against the SME

	Win	Draw	Loss
High-Time	**14** **.175**	**16** **.200**	**50** **.625**
Low-Time	**5** **.063**	**17** **.217**	**57** **.722**
	.12	**.21**	**.67**

Discussion

The expertise of the SME was evidenced by the fact that he won 67% of his engagements against the high-time and low-time pilots while losing only 12% of his sorties. As expected, the SME followed his own rules, as depicted by ISAAC, more consistently than did other pilots. The SME's behavior matched that prescribed by ISAAC in nearly 80% of the available opportunities. This is impressive when one considers that the opponents were attempting to prevent the SME from following some of the rules. For example, when offensive, ISAAC states that the pilot should continue to point toward the bogey and to reduce angle off the tail (AOT). In this circumstance, the opponent tries to increase AOT and prevent the fighter from pointing at him.

All pilots, including the SME, followed ISAAC rules more frequently when they won simulated air combat than when they lost. This result was consistently significant across high and low-time pilots, and across the initial conditions of line abreast and head on, suggesting that adhering to ISAAC rules increases the likelihood of winning air combat. High-time pilots did not adhere to ISAAC rules more frequently than did low-time pilots. However, variables such as recency of flying time or combat training were not controlled in this sample of pilots.

A more detailed analysis of ISAAC output revealed a few rules that were followed much more consistently by the SME than by other pilots. The SME was more successful at placing the bogey on the PVS immediately after the head-on passes, and then "maxing Gs". This allowed the SME to turn faster than the bogey and to obtain a nose-position advantage at the subsequent head-on pass. The nose-position advantage afforded the SME more time offensive than his opponent, increasing the likelihood of a successful missile or gun shot.

With minor enhancements, ISAAC will be used as a performance measurement system, capable of providing diagnostic feedback to pilots practicing 1v1 air combat in either the SAAC or on instrumented ranges.

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